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RESEARCH MEMORANDUM

REMOVAL OF SECONDARY-FLOW ACCUMULATIONS IN A TWO-DIMENSIONAL TURBINE NOZZLE PASSAGE BY BOUNDARY-LAYER BLEED

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REMOVAL OF SECONDARY-FLOW ACCUMULATIONS IN A TWO-DIMENSIONAL TURBINE NOZZLE PASSAGE BY BOUNDARY-LAYER BLEED

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SUMMARY

Boundary-layer bleed through a slot placed at the juncture of the suction surface and end wall was investigated herein to determine whether bleed in this manner could be used to prevent the local accumulation of boundary-layer fluids due to secondary flows. The results obtained with a single-passage parallel-end-wall nozzle indicate that boundary-layer bleed along this juncture can prevent this accumulation. It was also found that bleed-slot geometry and position and bleed pressure can markedly influence the bleed weight flow and the effectiveness of the bleed slot. Boundary-layer bleed applied in this manner to a turbine stator thus offers a means of investigating the effect of these loss regions on turbine rotor performance; however, the bleed weight flow for an annular cascade remains to be determined.

INTRODUCTION

Recent investigations indicate that stator secondary flows, in causing localized accumulations of low-energy fluid, may be a major contributor to the aerodynamic losses in a turbine (ref. 1). Radial and circumferential surveys of total pressure and total temperature taken at the exit of a turbine indicate large regions of low local efficiency. The cause of these low local efficiencies was attributed in reference 1 to the regions of low-energy stator flow passing through the rotor.

In view of these findings, it is desirable to evaluate quantitatively the effect of these localized regions of low-energy flow on over-all turbine performance. This evaluation may be accomplished through a reduction or elimination of these regions of low-energy flow. This in turn may be accomplished by application of boundary-layer bleed in the region where the boundary-layer fluids accumulate. The movement of the boundary-layer fluid on the passage end wall and its accumulation into a core of low-energy flow along the juncture of the suction surface and passage end wall are shown schematically in figure 1. From this figure it appears that bleed along this juncture may be effective in removing the boundary-layer fluids before they can accumulate. If a quantitative evaluation verifies the qualitative findings of reference 1, finding effective means of minimizing this source of turbine loss becomes even more important. Boundary-layer bleed in the manner just described appears promising as a means of accomplishing this evaluation, while its actual application to a turbine may or may not be practical.

This investigation was conducted at the NACA Lewis laboratory to determine whether bleed along the juncture of the suction surface and end wall can be effectively used to prevent the accumulation of boundary-layer fluids in this region. Included in the investigation is a study of various slot sizes and slot locations and bleed pressures in order to obtain an indication as to the bleed weight flow required. The investigation was conducted at a nozzle-exit Mach number of unity. Surveys of total pressure were made just downstream of the nozzle exit. The contours of constant total-pressure ratio obtained from the surveys at the nozzle exit with the bleed slot blocked off are compared with contours obtained from surveys of the nozzle with the various bleed configurations, in order to evaluate the effectiveness of each configuration.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

The apparatus used in this investigation (fig. 2) consisted of a single-passage nozzle mounted on the end of a 3-foot length of 15-inch-diameter pipe. An isometric drawing of the single-passage nozzle is shown in figure 3. The nozzle was designed with parallel end walls and to turn the flow 60°. The nozzle throat area was 3 square inches. A boundary-layer-removal slot was provided along the juncture of the suction surface and one of the end walls and constructed so that the slot configuration could be quickly and easily altered. In order to assure two-dimensional flow into the nozzle, an area convergence from pipe to nozzle inlet of 97 percent was used.

Instrumentation was provided to determine the inlet total pressure and total temperature, the total-pressure variation across the nozzle outlet, the bleed pressure, and the bleed weight flow. The inlet total temperature was measured with an unshielded thermocouple placed in the center of the air ducting upstream of the nozzle inlet. The inlet total pressure was measured with a shielded total-pressure probe placed 2 feet upstream of the nozzle inlet and at the center of the pipe. The outlet total-pressure variation was measured with a hook-type total-pressure probe mounted in an actuator so that the probe could be moved to any point in the plane of the nozzle exit. The nozzle-exit total pressures were transmitted through a pressure transducer and recorded against probe travel on an automatic curve tracer. The bleed pressure was measured with a static-pressure tap placed in the bleed plenum chamber. The bleed weight flow was measured with a calibrated rotameter. All pressures except the outlet total pressure were measured with a mercury manometer.

With the inlet total pressure set so that the nozzle was just choked, total-pressure surveys of half the jet stream were made in a plane just downstream of the nozzle exit, as shown in figure 2. These surveys were taken so that the total-pressure contours were completely defined. The bleed rate for a given slot configuration was controlled by varying the static pressure in the bleed plenum chamber. A summary of the slot configurations investigated herein is presented in table I. For comparison with contours obtained from the various slot configurations, the nozzle was first run with the boundary-layer-removal slot blocked off. The ideal nozzle weight flow was calculated using measured values of inlet total temperature and total pressure and assuming a flow coefficient of unity at the choked nozzle throat.

RESULTS AND DISCUSSION

The results obtained from the investigation of the single-passage nozzle with the various bleed-slot configurations are presented in figures 4 to 7. These figures show contours of constant total-pressure ratio measured across the nozzle from the inlet to a plane just at the exit of the nozzle for half the jet stream.

The contours of total-pressure ratio obtained with the bleed slot blocked off are given in figure 4 to illustrate the effect of secondary flows on the boundary layers of this particular nozzle configuration. This figure indicates that the end-wall boundary-layer fluids are being transported toward the suction surface of the passage. As a result, the end-wall boundary-layer thickness increases from the pressure surface to the suction surface. Further, the boundary layer on the suction surface, a short distance from the end wall, is considerably thicker than the boundary layer on the rest of the suction surface. Thus, another manifestation of these secondary flows is the formation of a localized region of low-energy flow on the suction surface. The distance these total-pressure-ratio contours extend into the passage beyond the rest of the suction-surface boundary layer is an indication of the amount of the additional boundary-layer fluids present in this region as the result of end-wall secondary flows. The boundary-layer fluids also appear to be spilling out of the corner between the suction surface and the end wall. This phenomenon is attributable to overturning of the lower-momentum fluids similar to that observed in reference 2. The jet stream appears to be larger than the nozzle outlet because of the effects of mixing of the jet stream with the surrounding air and because the probe is a finite size.

Effect of Bleed Pressure

The survey results obtained by bleeding the end-wall boundary layer through a bleed slot of fixed geometry are shown in figure 5 (tests

IIa to e of table I). The static pressure to which the boundary layer was bled was varied from that required to completely choke the bleed slot to a pressure where recirculatory flows through the bleed slot took place. The slot geometry used in this particular test consisted of a full-length slot (portions A through E as shown in the figure of table I), which varied in height from 0.020 inch at the nozzle inlet to 0.040 inch at the nozzle outlet. This combination of length and height variation resulted in a bleed-slot flow area of 0.032 of the nozzle throat area. A comparison of these figures with figure 4 indicates that, when the bleed pressure is sufficiently low (tests IIa to c), the localized accumulation of low-energy flow noted in figure 4 does not 3726
form to any large extent, as indicated in figures 5(a) to (c) by the thickness of the suction-surface boundary layer. The figures indicate that the suction-surface boundary layer in the region of the end wall is comparable with that along the rest of this surface.

When the bleed pressure was approximately equal to the nozzle-outlet pressure (test IId, fig. 5(d)), there was insufficient boundary-layer removal to completely prevent the formation of the region of low-energy flow, as is indicated by a slightly thicker suction-surface boundary layer near the end wall. For bleed pressures greater than the outlet static pressure (test IIe, fig. 5(e)), the region of low-energy flow was increased to the point that it was even larger than that noted in figure 4 with the bleed slot blocked off. This phenomenon is probably due to recirculating flows through the slot as a result of the variation of local nozzle static pressure from above the bleed pressure over the first portion of the slot to below the bleed pressure over the nozzle-outlet portion of the slot. Thus, where the nozzle local static pressure is above the bleed pressure, the bleed flow moves out of the nozzle; whereas, in the regions where nozzle local static pressure is below the bleed pressure, the flow moves back into the nozzle. The reentrance of air into the nozzle in the region of the nozzle outlet appears to cause a major disturbance in the flow in that region.

For tests IIa to e, the bleed weight flow varied from 0.020 of the ideal nozzle weight flow with bleed slot completely choked to 0.004 for the condition of recirculating flows.

Effect of Bleed-Slot Height

Bleed-slot height was next varied to determine whether the bleed weight flow could be reduced while still maintaining effective control of the formation of the localized region of low-energy flow. For these tests a full-length bleed slot was used and bleed pressure was maintained constant at a value sufficient to choke the bleed slot. The slot heights selected for this phase of the investigation resulted in bleed-slot flow areas of 0.023 and 0.018 of the nozzle throat area. The survey results obtained with bleed through these slots are given in figures 6(a) and (b) (tests IIIa and b of table I, respectively). Comparison of these figures with figure 5(a) indicates that the smallest bleed slot (test IIIb, fig. 6(b)) was not quite as effective as the larger slots in preventing the formation of the region of the low-energy flow on the suction surface. This is indicated by the slight thickening of the suction-surface boundary layer in the region of the end wall in figure 6(b). Comparison of the contours of total-pressure ratio obtained for the two larger slots (figs. 5(a) and 6(a)) indicates that both slot configurations were about equally effective. The smaller slot, as indicated by bleed weight flow for these two tests, removes considerably less of the high-energy fluids.

Effect of Slot Length and Position

The effect of slot length and position on the low-energy flow formations was determined with the slot configuration that had a bleed flow area of 2.3 percent of the nozzle throat area in the previous phase of this investigation. Survey results at the nozzle exit with various portions of the bleed slot blocked off are given in figure 7 (tests IVa to e in table I). The bleed pressure was again maintained at a value sufficient to choke the entire bleed slot.

The contours shown in figure 7(a) are the survey results obtained with only the last two-thirds of the bleed slot open (portions C through E, table I). Comparison of figure 7(a) with figure 6(a) indicates that effectiveness of the slot was not impaired to any large extent by blocking off the first third of the bleed slot, even though the bleed weight flow was reduced by about one-half.

Figure 7(b) presents the survey results obtained with only that part of the bleed slot behind the throat of the nozzle being open (portions D and E in table I). Inspection of this figure indicates that blocking off the first two-thirds of the bleed slot reduced the effectiveness of the bleed slot.

In the next test the bleed slot ahead of the nozzle throat was left open and that behind the throat was blocked off. The survey results of this test are presented in figure 7(c), which indicates that blocking off the bleed slot downstream of the throat also has an adverse effect on bleed-slot effectiveness. Thus, secondary flows are still taking place downstream of the nozzle throat.

From the preceding results, it appears that the end portions of this bleed slot are taking in some high-energy fluids. The survey results obtained with the end portions (sections A and E in table I) of the bleed slot blocked off are given in figure 7(d). Comparison of this figure with figure 6(a) indicates that shortening the slot on either end did not impair its effectiveness; and, with the bleed slot choked, 0.010 of the ideal nozzle weight flow was removed.

It is probable that a further reduction in the bleed weight flow may be achieved by further changes in the length of the slot or by a modification of the slot-height variation, which was not altered throughout this investigation. However, it is felt that these adjustments will only result in minor reductions in bleed weight flows.

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CONCLUDING REMARKS

The results of this investigation indicate that the highly localized regions of low-energy flow resulting from secondary flows in a turning passage may be controlled by bleed through a slot placed along the juncture of the suction surface and end wall. For this particular nozzle configuration and the best slot configuration tested, approximately 0.010 of the ideal nozzle weight flow was bled to prevent the formation of a low-energy flow region on the suction surface at each end wall. Bleed in the region just upstream and just downstream of the nozzle throat was found to be the most effective location. It was also found that bleed-slot geometry and bleed pressure can greatly influence the bleed weight flow and bleed-slot effectiveness. The application of boundary-layer bleed to a turbine stator offers a means of investigating the effect of these localized regions of low-energy flow on turbine rotor performance. It should be noted, however, that the bleed weight flow required in an annular cascade remains to be determined.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 12, 1955

REFERENCES

1. Whitney, Warren J., Buckner, Howard A., Jr., and Monroe, Daniel E.: Effect of Nozzle Secondary Flows on Turbine Performance as Indicated by Exit Surveys of a Rotor. NACA RM E54B03, 1954.

2. Rohlik, Harold E., Kofskey, Milton G., Allen, Hubert W., and Herzig, Howard Z.: Secondary Flows and Boundary-Layer Accumulations in Turbine Nozzles. NACA Rep. 1168, 1954. (Supersedes NACA TN's 2871, 2909, and 2989.)

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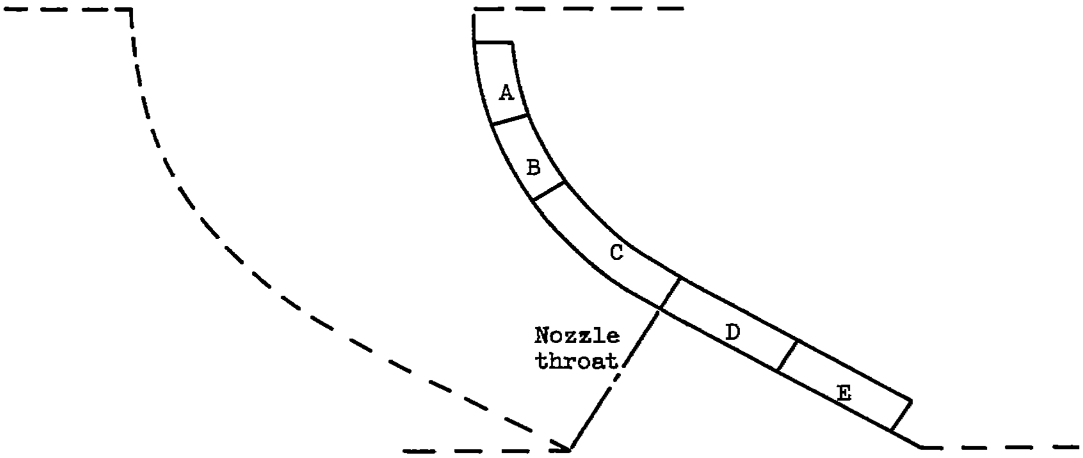
TABLE I. - SUMMARY OF SLOT CONFIGURATIONS



Test	Figure	Slot positions	Slot height: Upstream end	Slot height: Downstream end	Ratio of slot flow area to nozzle-throat flow area	Ratio of bleed pressure to nozzle-outlet static pressure	Ratio of bleed weight flow to ideal nozzle weight flow
I	4	None	-----	-----	-----	-----	-----
IIa	5(a)	A through E	0.020	0.040	0.032	0.51	0.020
b	(b)	↓	↓	↓	↓	.68	.019
c	(c)					.84	.017
d	(d)					.99	.012
e	(e)					1.13	.004
IIIa	6(a)	A through E	0.012	0.032	0.023	0.48 } Bleed slot choked	0.015
b	(b)	A through E	.008	.028	.018	.51	.010
IVa	7(a)	C through E	0.013	0.032	0.018	0.47 } Bleed slot choked	0.008
b	(b)	D through E	.022	.032	.013	.47	.007
c	(c)	A through C	.012	.022	.010	.47	.007
d	(d)	B through D	.013	.030	.014	.49	.010

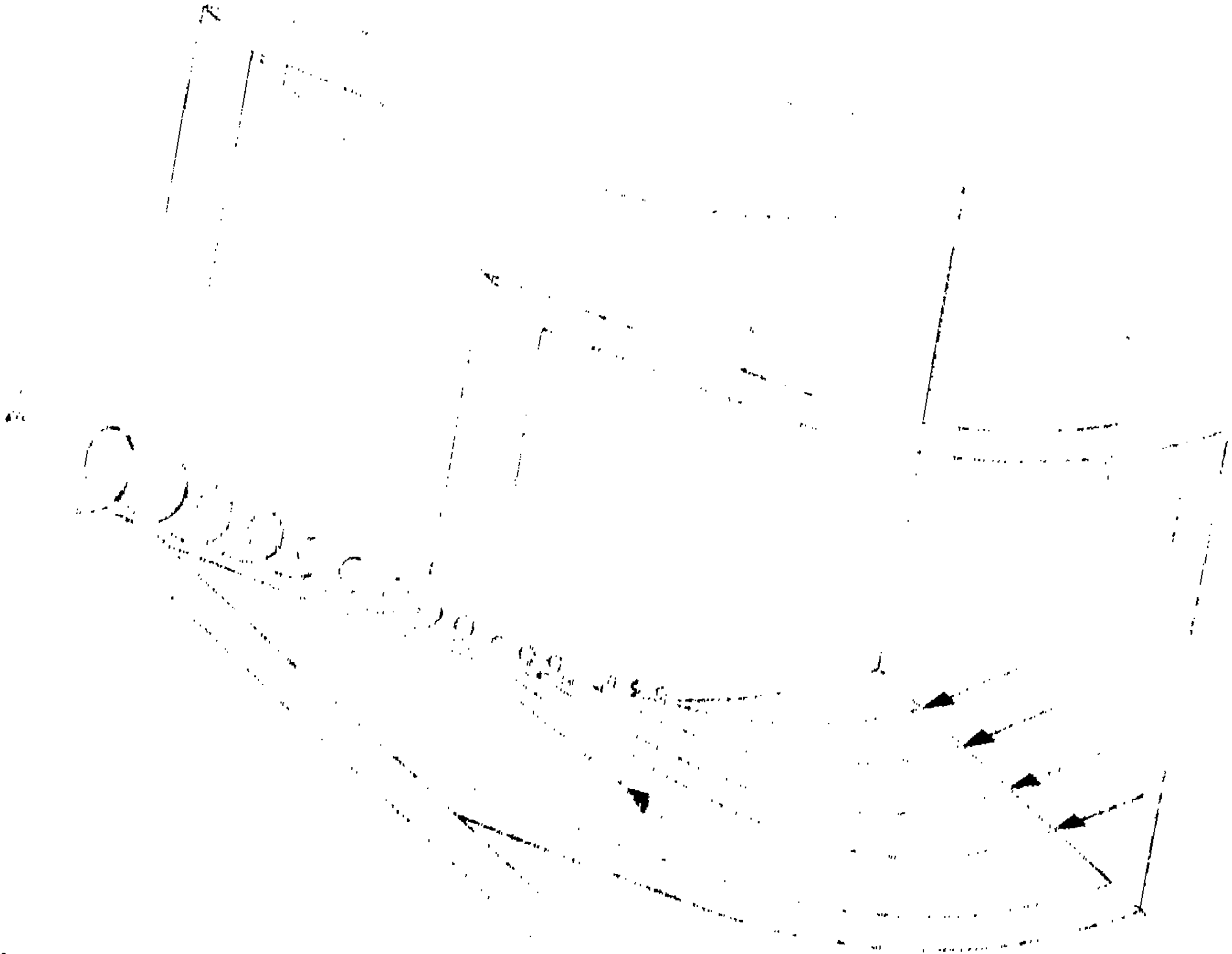


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Figure 1. - End-wall boundary-layer movements in a typical two-dimensional turning passage.

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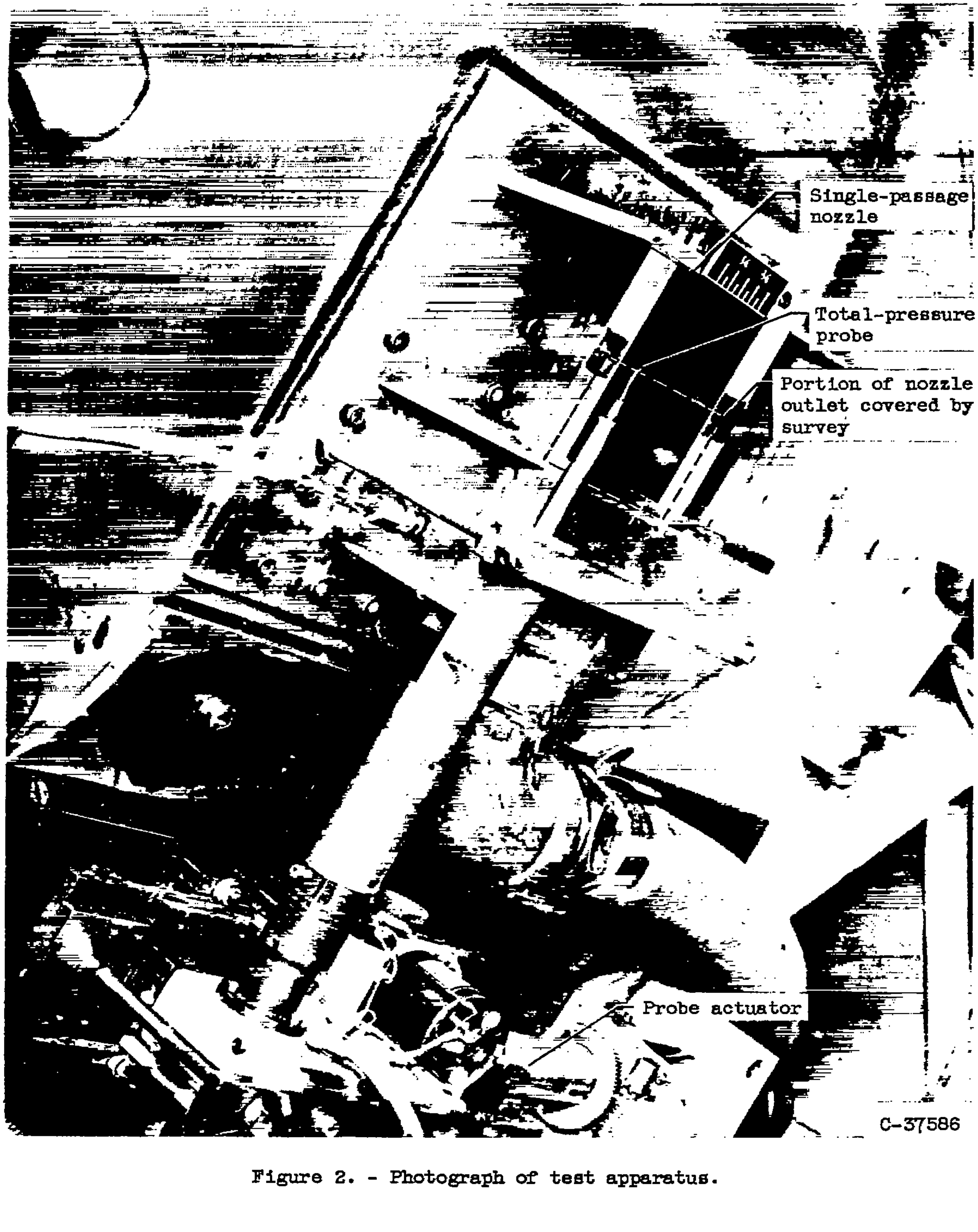

Figure 2. - Photograph of test apparatus.

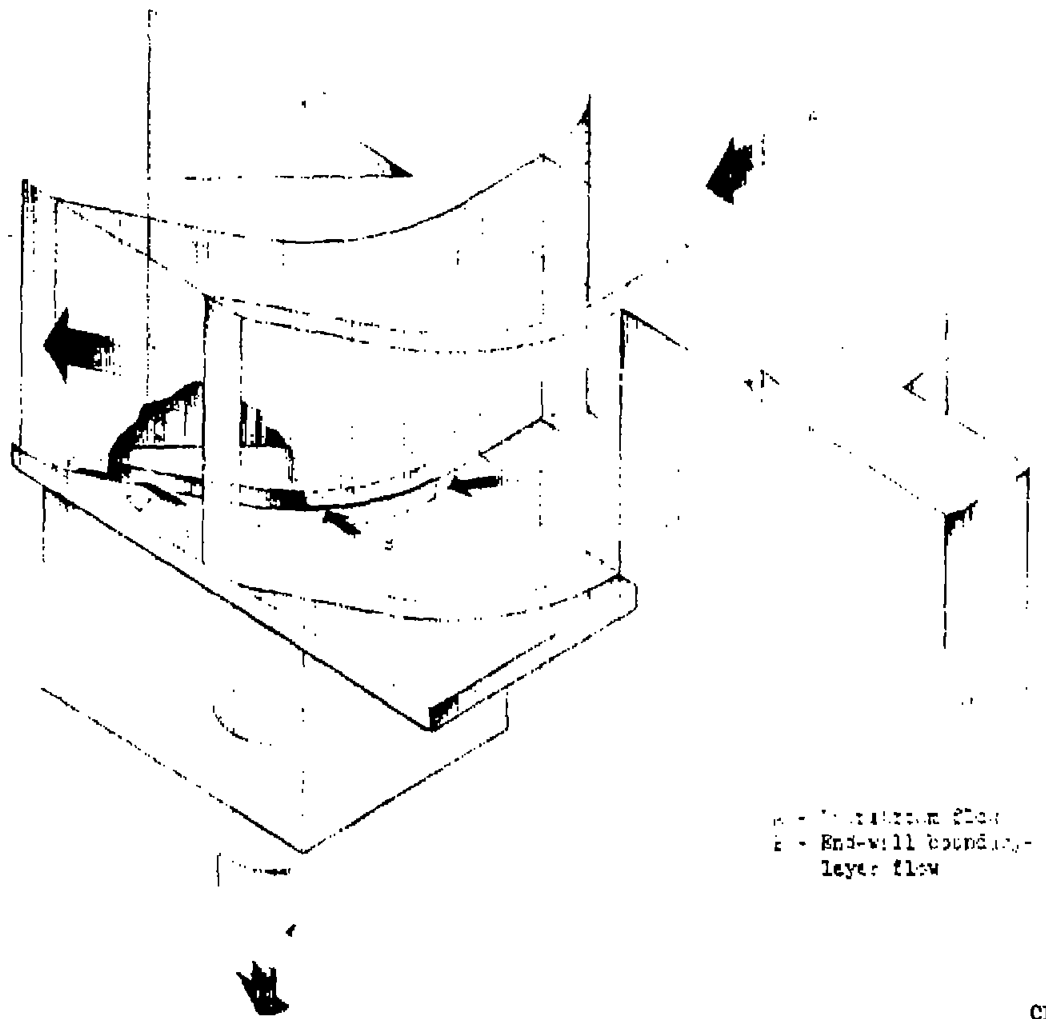

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Figure 3. - Isometric sketch of test nozzle.

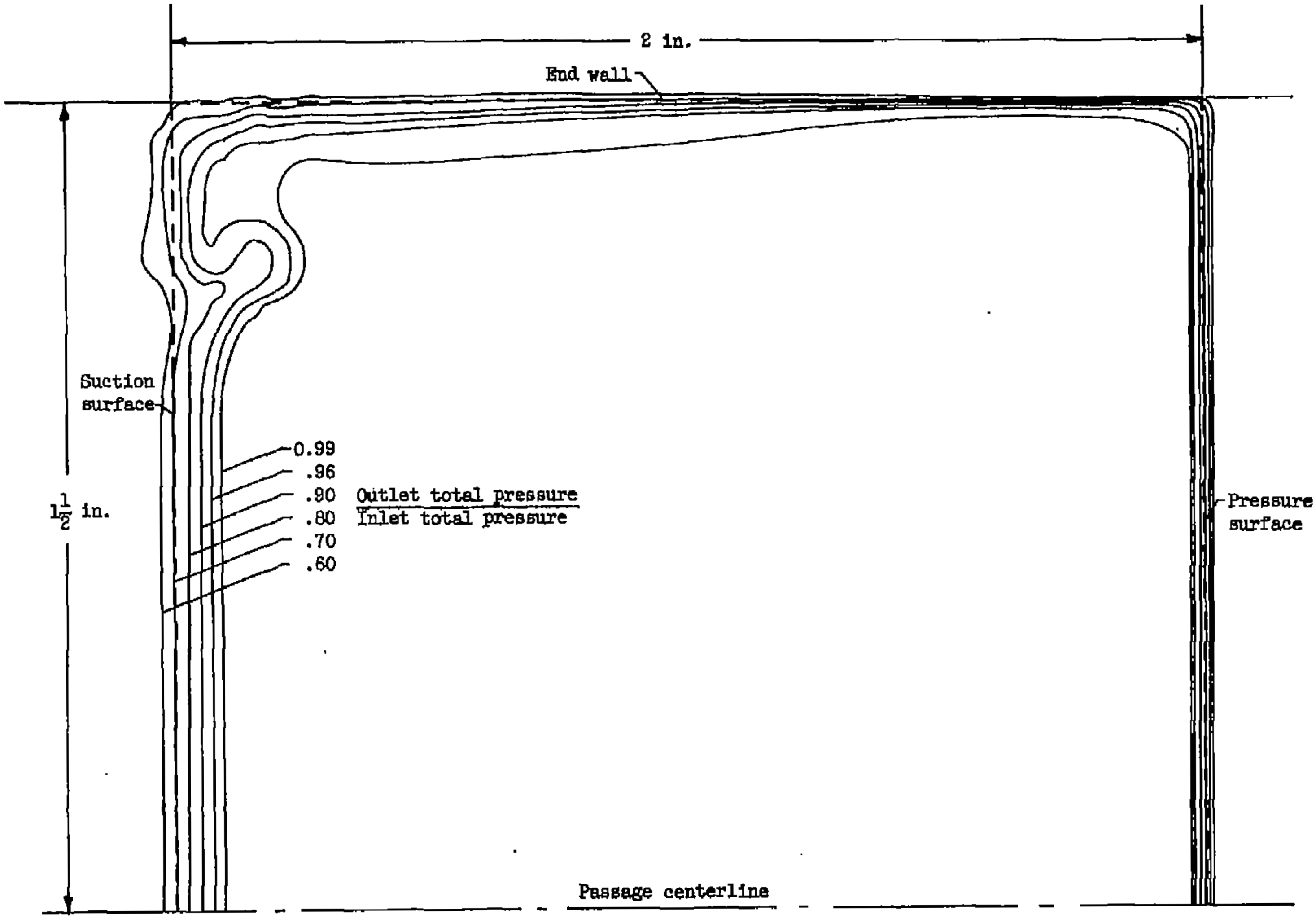

Figure 4. - Effect of end-wall secondary flow on nozzle total-pressure-ratio contours. Test I.

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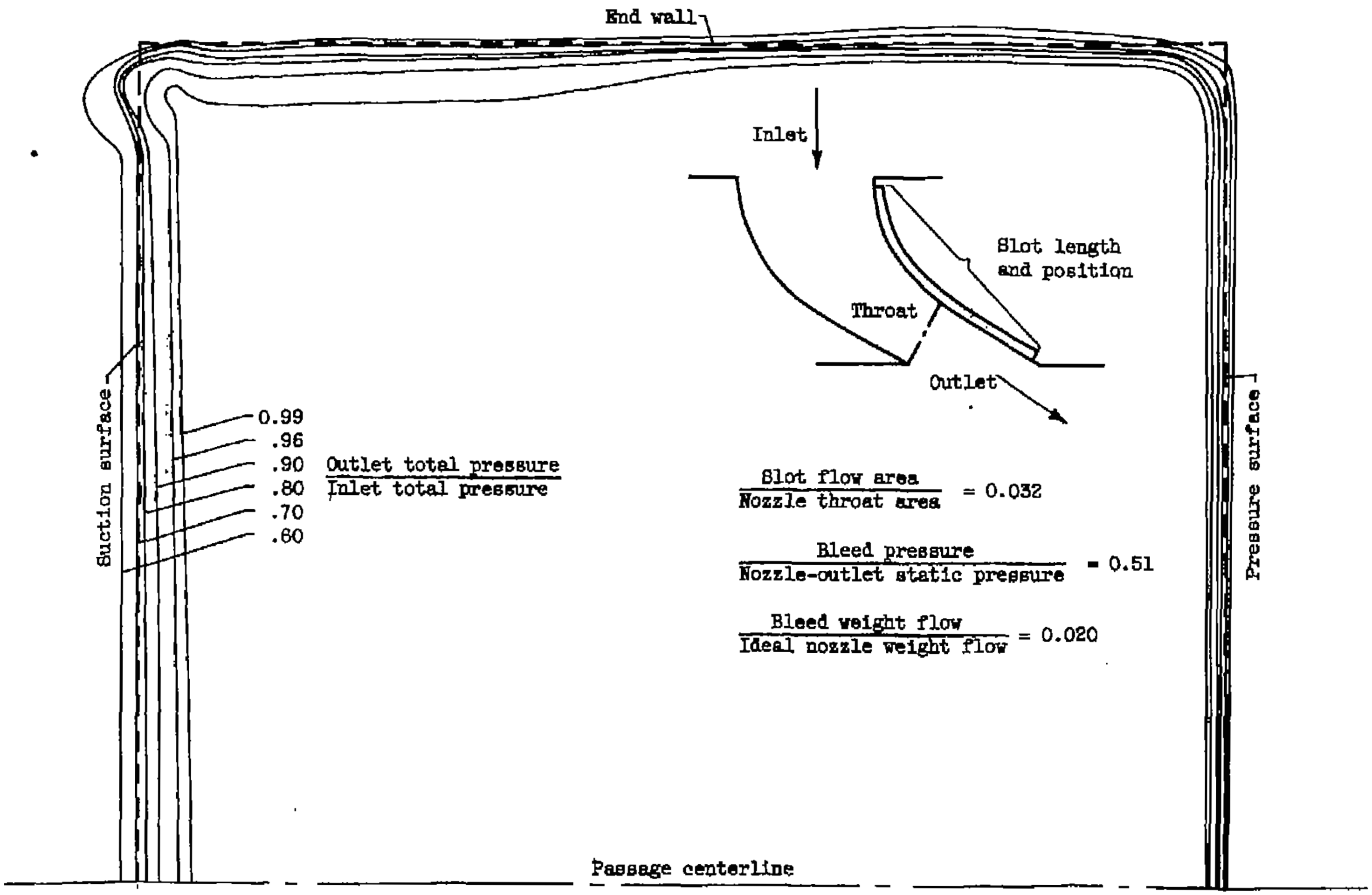
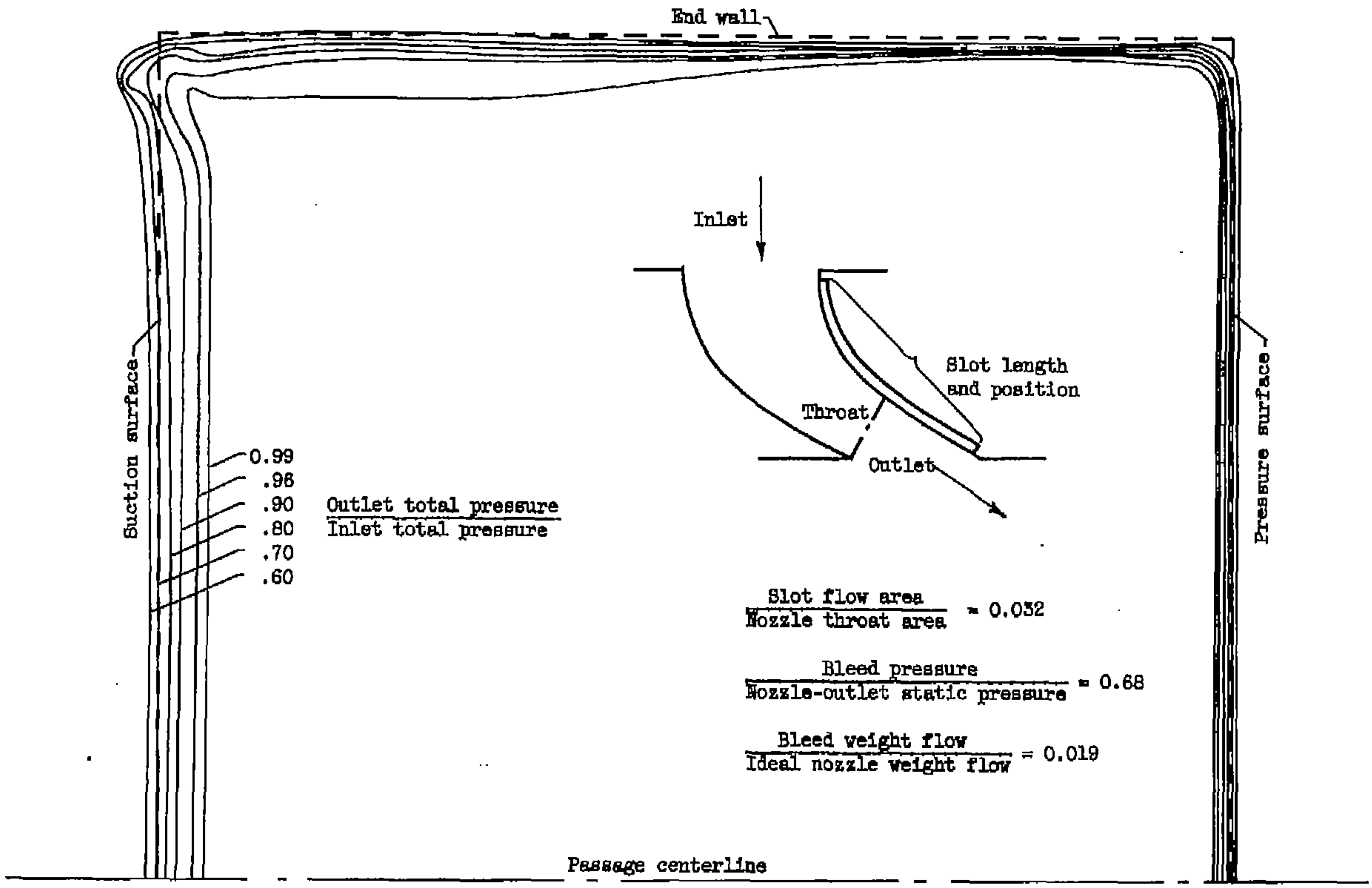


(a) Test IIa.

Figure 5. - Effect of bleed pressure on nozzle total-pressure-ratio contours for bleed slot of fixed geometry.

[redacted]



(b) Test IIb.

Figure 5. - Continued. Effect of bleed pressure on nozzle total-pressure-ratio contours for bleed slot of fixed geometry.

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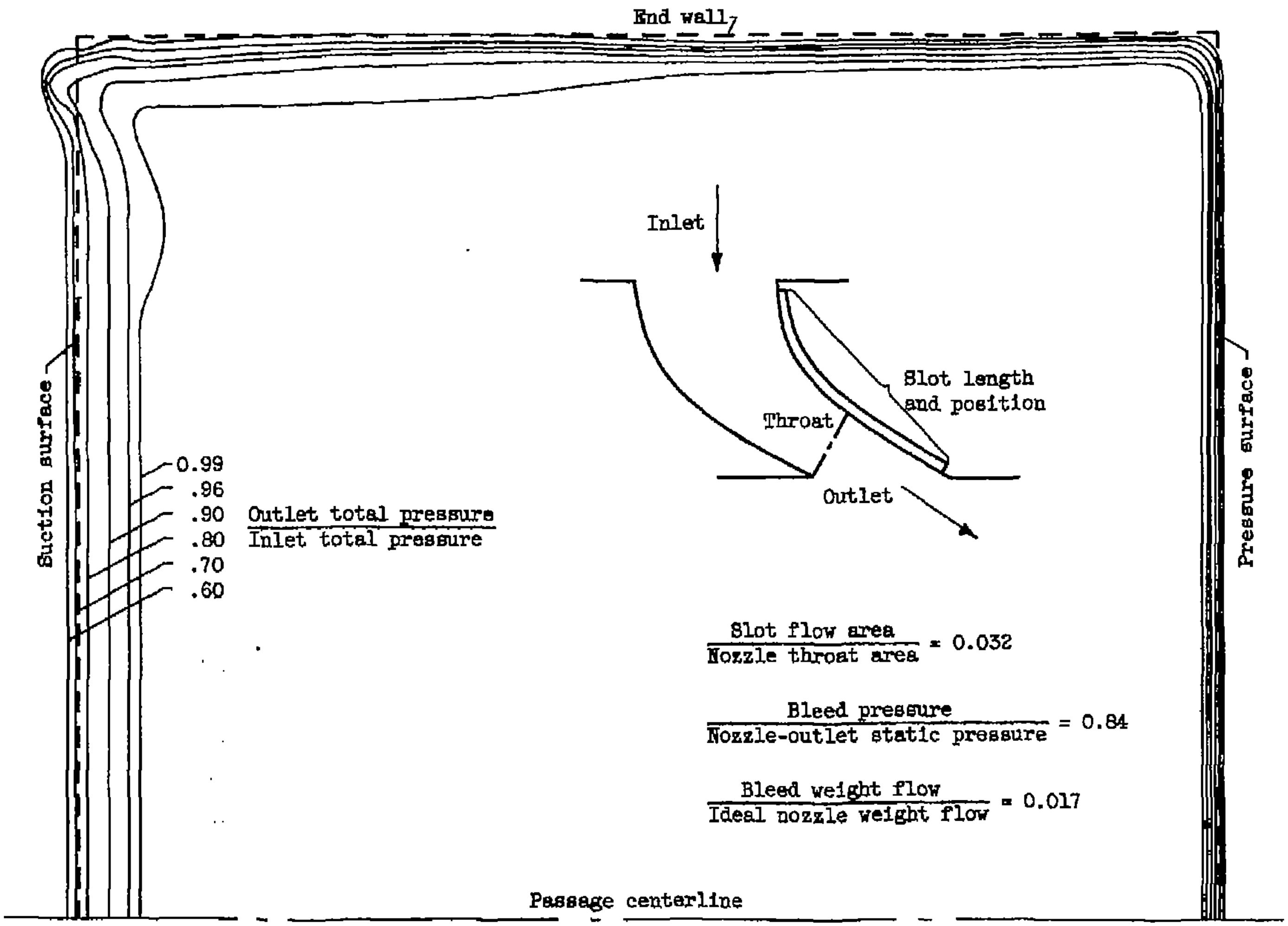

(c) Test IIc.

Figure 5. - Continued. Effect of bleed pressure on nozzle total-pressure-ratio contours for bleed slot of fixed geometry.

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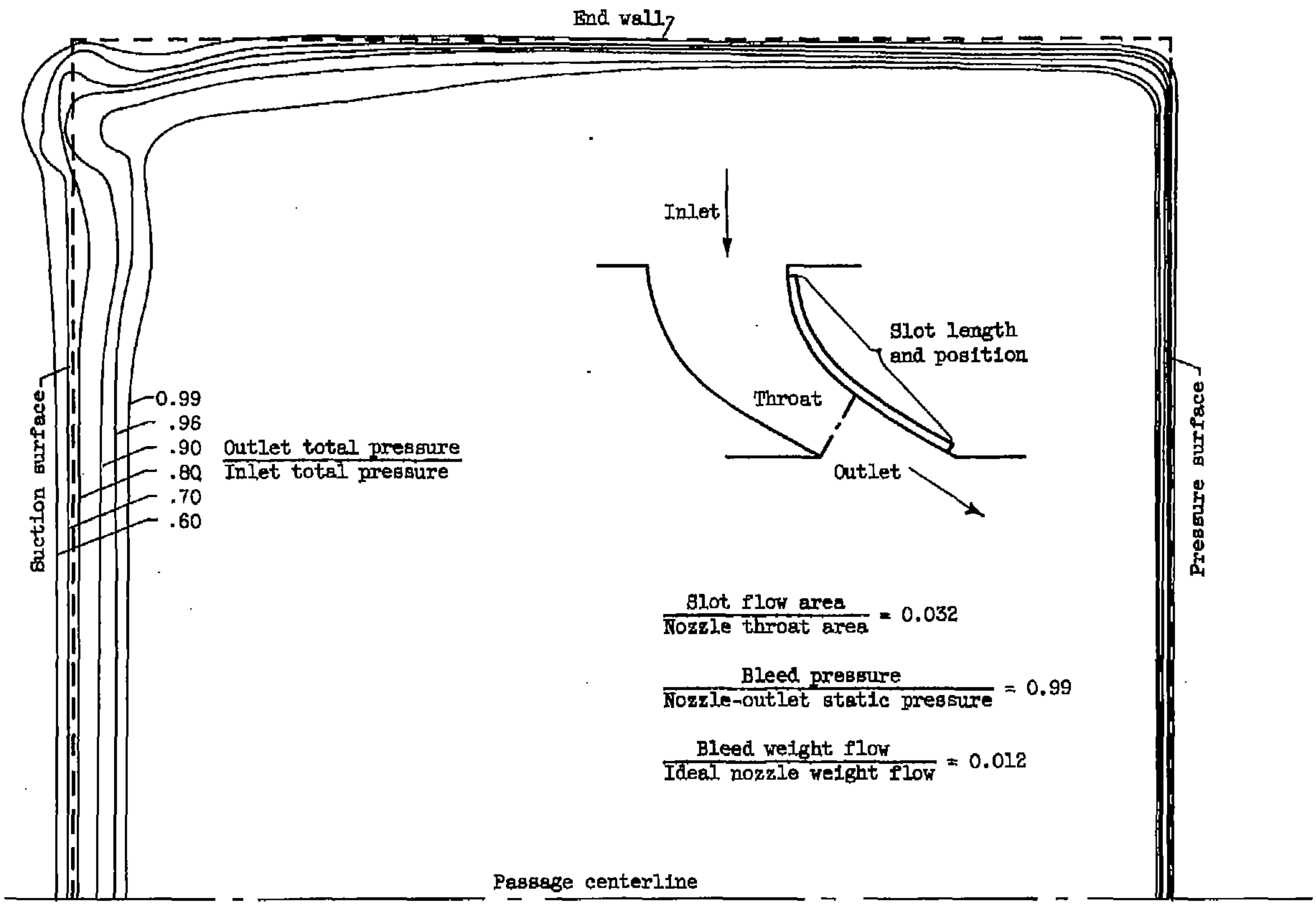
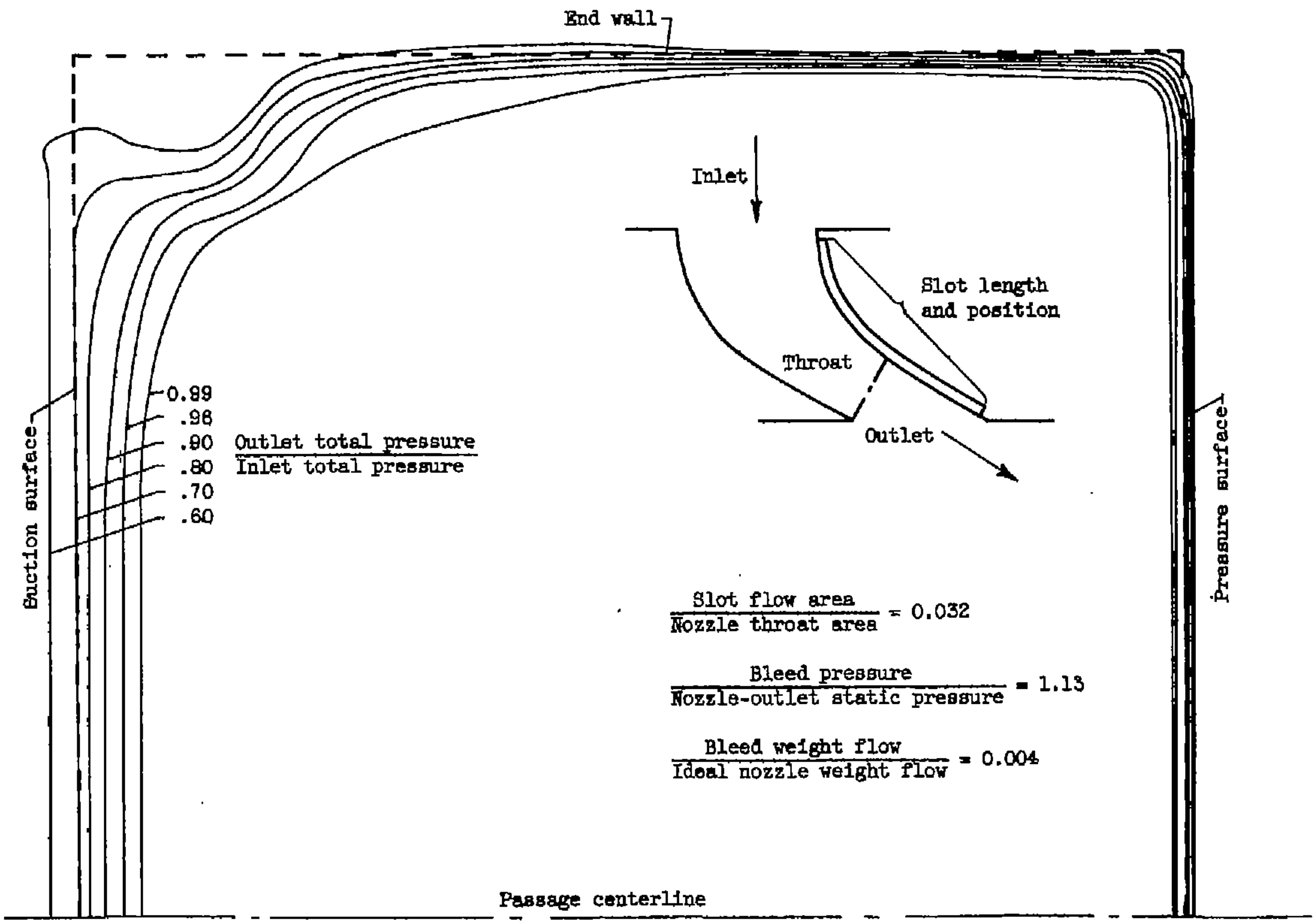


(d) Test IId.

Figure 5. - Continued. Effect of bleed pressure on nozzle total-pressure-ratio contours for bleed slot of fixed geometry.

[redacted]



(e) Test IIe.

Figure 5. - Concluded. Effect of bleed pressure on nozzle total-pressure-ratio contours for bleed slot of fixed geometry.

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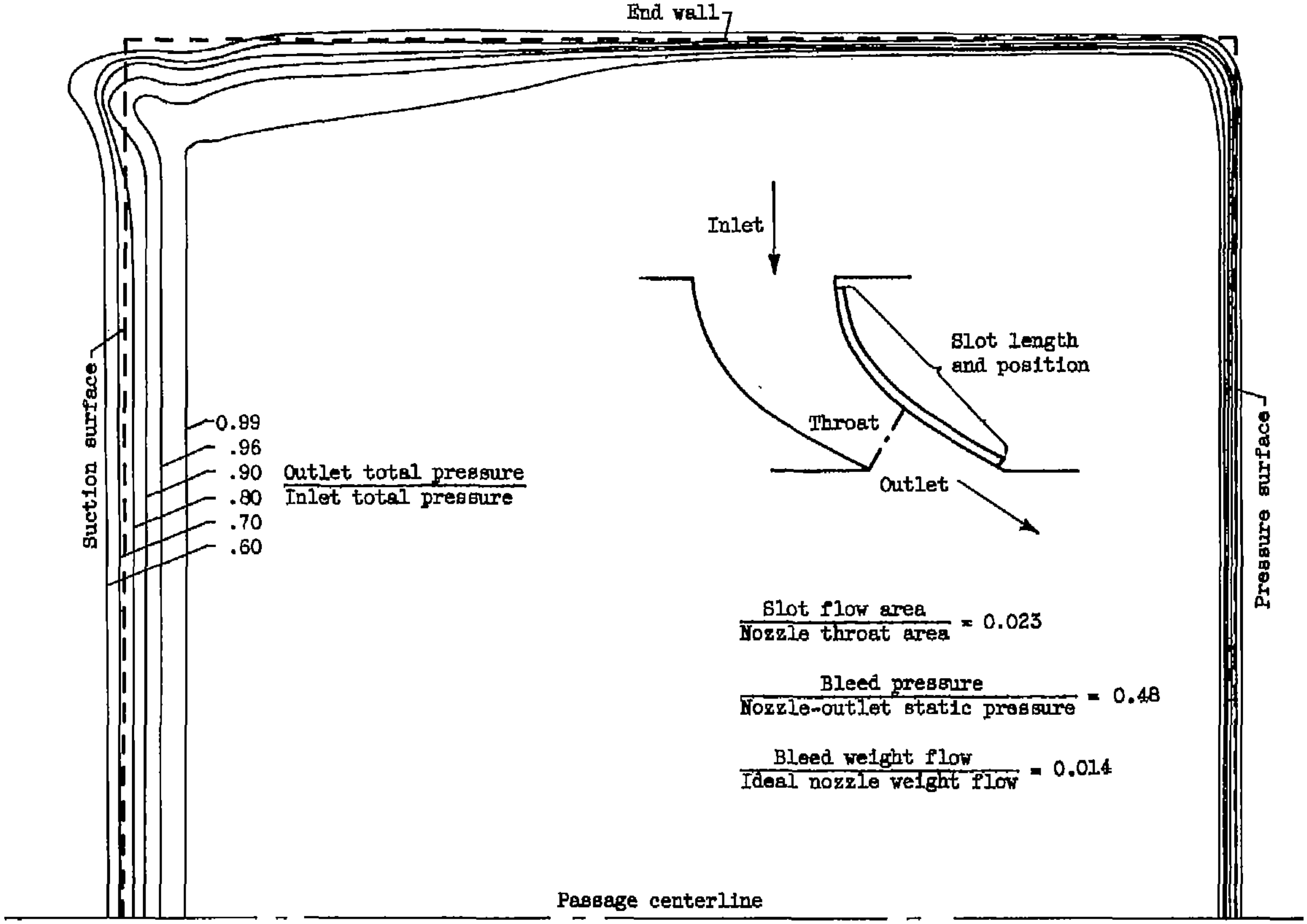
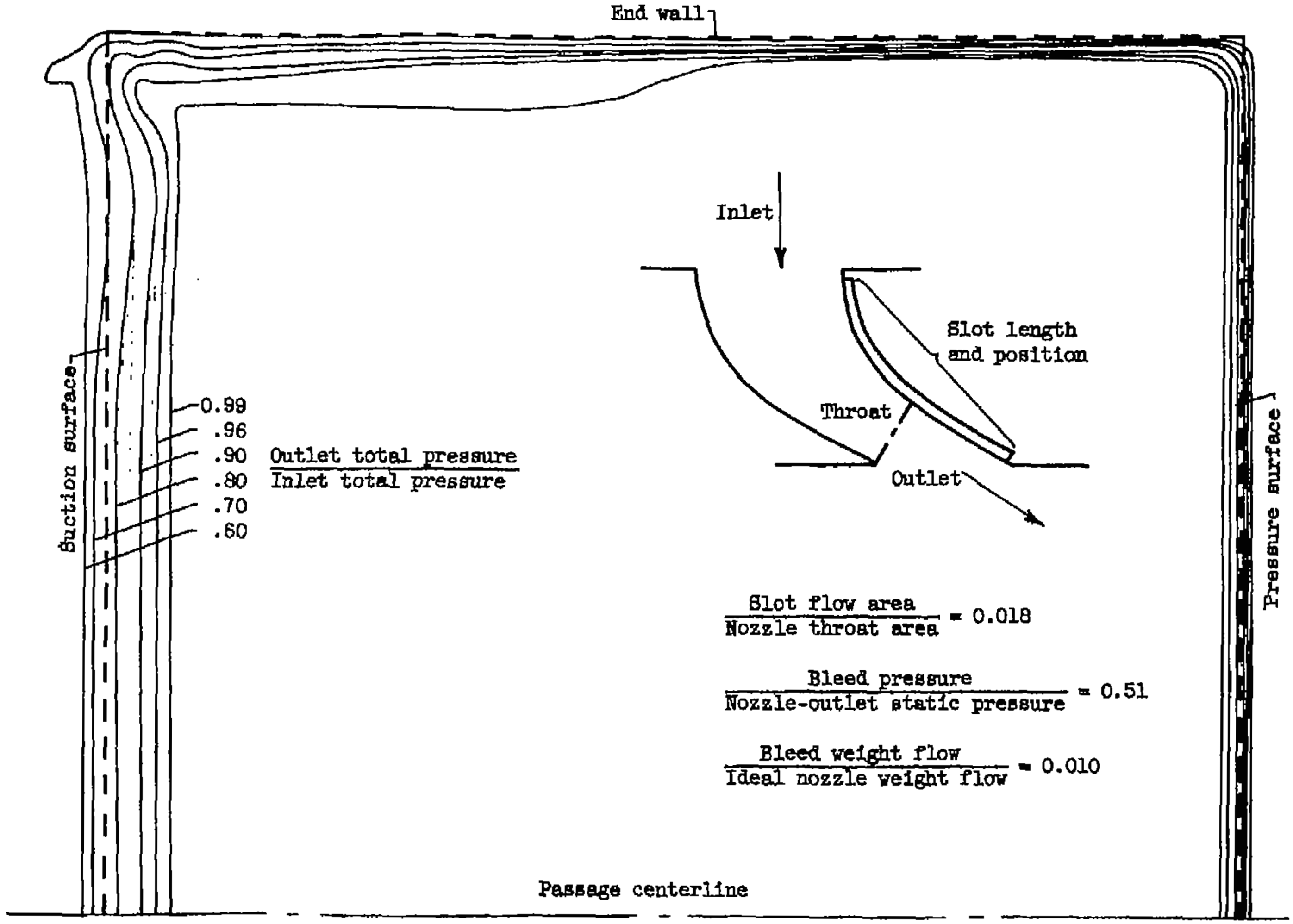


(a) Test IIIa.

Figure 6. - Effect of bleed-slot height on nozzle total-pressure-ratio contours for choked bleed slot of fixed length.



(b) Test IIIb.

Figure 6. - Concluded. Effect of bleed-slot height on nozzle total-pressure-ratio contours for choked bleed slot of fixed length.

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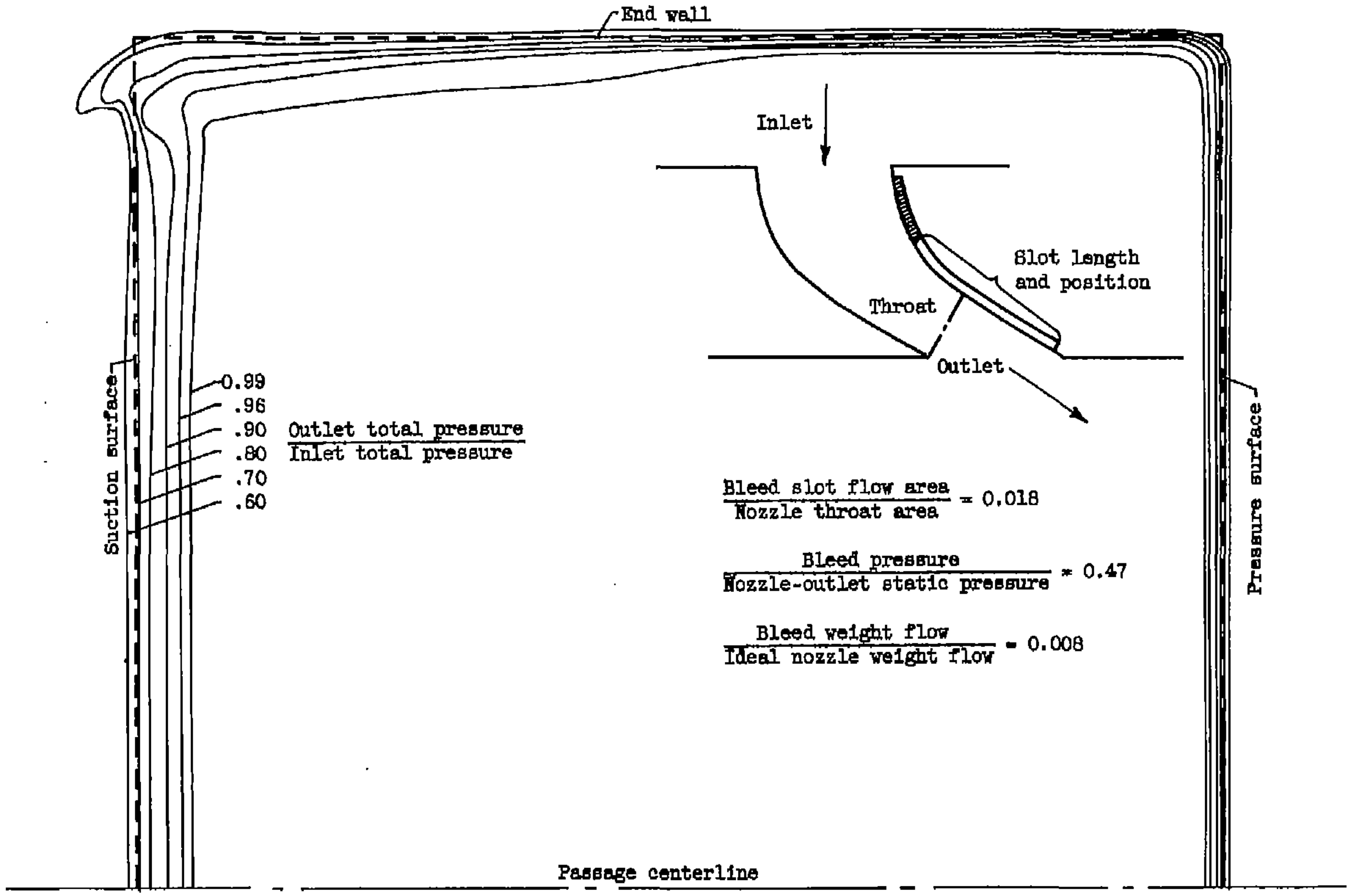

(a) Test IVa.

Figure 7. - Effect of slot length and position on nozzle total-pressure-ratio contours for choked bleed slot of fixed height.

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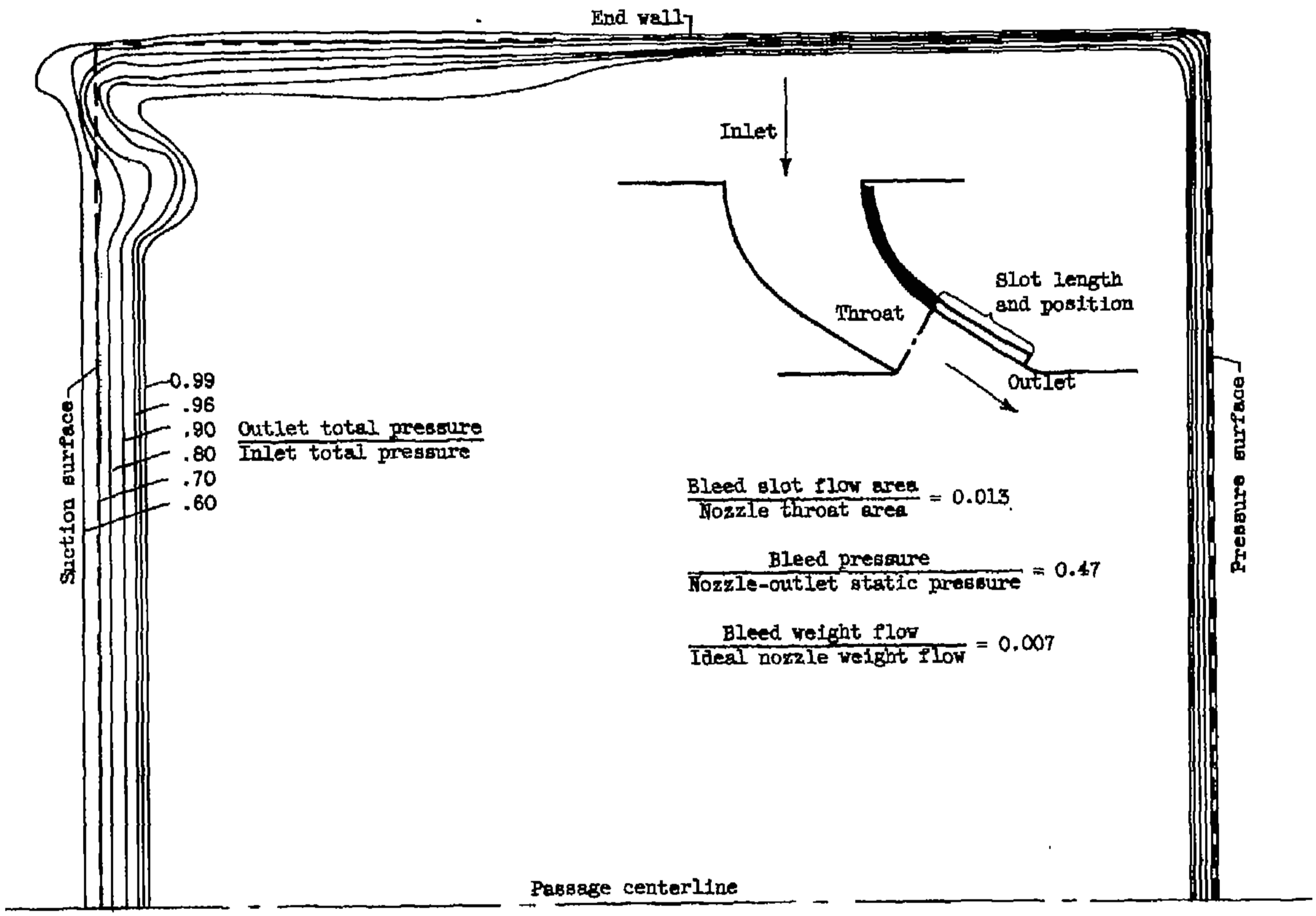
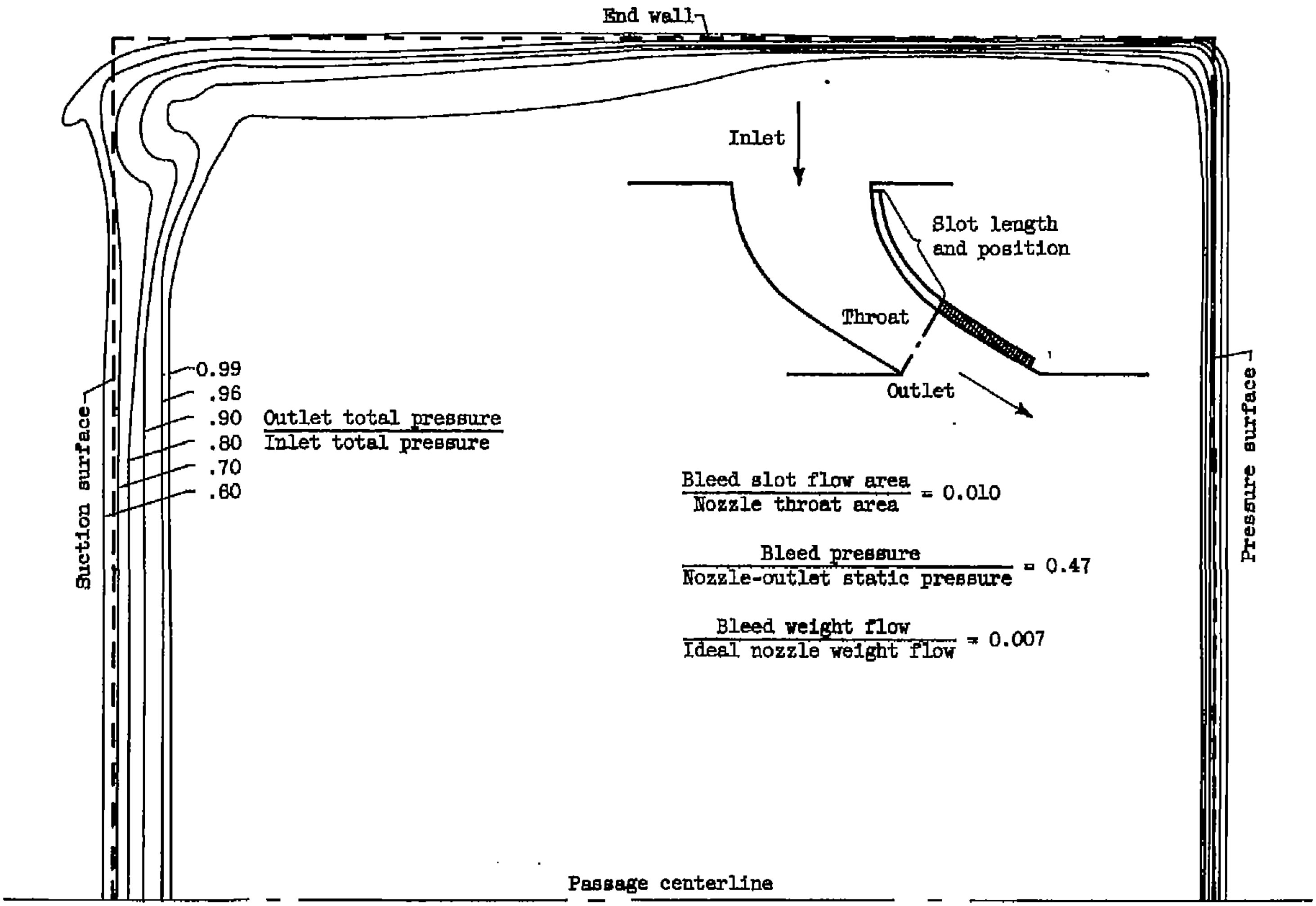


(b) Test IVb.

Figure 7. - Continued. Effect of slot length and position on nozzle total-pressure-ratio contours for choked bleed slot of fixed height.



(c) Test IVc.

Figure 7. - Continued. Effect of slot length and position on nozzle total-pressure-ratio contours for choked bleed slot of fixed height.

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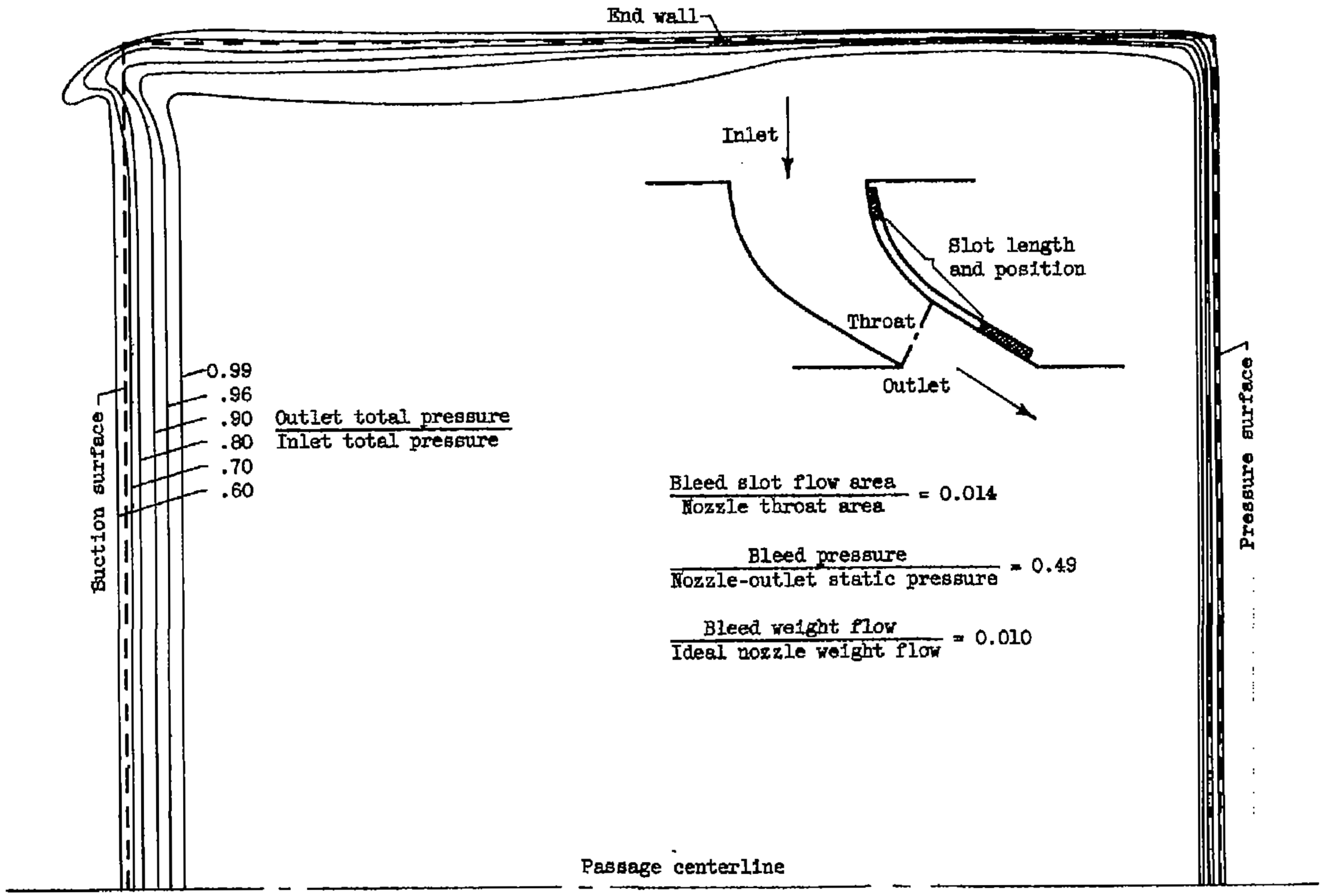

(d) Test IVd.

Figure 7. - Concluded. Effect of slot length and position on nozzle total-pressure-ratio contours for choked bleed slot of fixed height.

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